Waste Biomass Valor (2014) 5:147–155
DOI 10.1007/s12649-013-9227-x

ORIGINAL PAPER

CHP Gasification Systems Fed by Torrefied Biomass: Assessment of the Energy Performance

Dario Prando · Francesco Patuzzi · Paolo Baggio · Marco Baratieri

Received: 15 September 2012 / Accepted: 27 February 2013 / Published online: 9 March 2013
© Springer Science+Business Media Dordrecht 2013

Abstract The aim of this work is to assess the effect of torrefaction pre-treatment on the energy efficiency of cogeneration biomass gasification systems, using a multi-stage modelling approach. The gasification unit has been simulated by means of an enhanced gas–solid thermodynamic model assessing the theoretical yield and composition of the reaction products (syngas, char). Syngas utilization units for power generation have been coupled to the gasification stage considering the gas clean-up and heat recovery sections. The whole system has been then simulated proposing three different power generation units; internal combustion engine, gas turbine and combined cycle gas turbine. A parametric analysis has been performed varying feedstock, torrefaction and gasification temperatures, gasifying agent and evaluating the electrical and thermal efficiencies according to the different plant configurations. In particular, the effect of the torrefaction temperature on the system performance has been assessed. This theoretical analysis allowed the definition of some scale parameters useful for the feasibility assessment of energy conversion systems fed by torrefied biomass.

Keywords Gasification · CHP system · Torrefaction · Multistage simulation

D. Prando (✉) · F. Patuzzi · M. Baratieri
Faculty of Science and Technology, Free University of Bolzano, Bolzano, Italy
e-mail: dario.prando@natec.unibz.it

M. Baratieri
e-mail: marco.baratieri@unibz.it

P. Baggio
Department of Civil and Environmental Engineering, University of Trento, Trento, Italy

Introduction

In biomass-to-energy systems, torrefaction can represent an interesting pre-treatment, as it increases the feedstock energy content and its suitability for the subsequent thermal conversion processes, such as gasification. Furthermore, the opportunity of integrating biomass gasification in combined heat and power (i.e., CHP) generation systems is particularly interesting, especially for small-scale applications. In fact, biomass boiler and Rankine cycle are usually a valuable option for large size power plant that can be scaled down to 250 kW_{el} with the use of organic fluids. Smaller systems with an interesting efficiency can be obtained by the coupling of a gasifier with an internal combustion engine which can be scaled down to 30 kW_{el}. CHP systems based on biomass gasification represents a promising technological solution and a feasible alternative to biomass combustion, especially for small-scale applications. In this perspective, the integration of biomass gasification with high efficiency power generation systems is able to define competitive scenarios if compared with conventional biomass cogeneration. The increase of the systems efficiency, given by the implementation of these alternative technology, makes it feasible the development of energy models based on distributed cogeneration at sizes that have traditionally low efficiency.

The research concerning the coupling of biomass gasification with conventional power generators (gas engines and gas turbines) and with innovative generation systems (fuel cells) is well documented in the literature [1, 2]. Besides the development of mathematical models for a given biomass processing systems, the simulation of a complete energy conversion plant is usually carried out through process simulators that offer advantages in the evaluation of the process performance in different operating condition [3].

The evaluation of the overall system performance in terms of energy generation and usage still requires further research and development to assess effective implementation of the technologies as integrated in their complete energy chain (biomass pre-processing, biomass energy conversion, energy distribution, final usages).

The aim of this work is to perform a sensitivity analysis on the energy efficiency of cogeneration biomass gasification systems, taking into account torrefaction as a pre-processing stage. The assessment has been carried out developing a multistage object-oriented model based on enhanced thermodynamic routines applied to the reacting stages and supplemented with an evaluation of the energy fluxes arising from the other plant components.

Materials and Methods

Gasification Process Modelling

The pyrolysis/gasification of different biomass feedstock (both as received and torrefied) has been simulated through an enhanced thermochemical equilibrium model in order to characterize the syngas yield and composition. The model consists of a code written in Matlab environment that handle chemical reaction equilibria, implementing the Cantera software library, a collection of object-oriented software tools for problems involving chemical kinetics, thermodynamics and transport phenomena [4]. For detailed information about the implemented model it is worth to refer to [5].

Three different thermochemical conversion processes have been considered: pyrolysis, partial oxidation and steam gasification. The main process parameters that have been taken into account are: temperature, equivalence ratio (i.e., ER ratio between the oxygen fed to the gasifier and the stoichiometric quantity of oxygen needed for the complete oxidation of the species) and the steam to carbon ratio (i.e., SC ratio between the supplied steam and the carbon fraction present in the feedstock). The effects of these parameters have been investigated in the range 500–1,000 °C for temperature, 0.05–0.5 for ER and 0.5–5.0 for SC.

Torrefaction Data

Torrefaction is gaining a widespread interest in the last years, as confirmed by the high number of works that can be found in literature [6]. Some of the works reporting the elemental composition of torrefied biomass have been selected and have been collected reliable experimental data. The elemental composition, moisture content and heating value of different raw and torrefied biomass have been used as input of the thermochemical equilibrium model. In particular, the following feedstock have been tested: pine, bagasse, birch [7], reed canary grass, wheat straw, willow [8], pine wood chips and logging residue chips [9]. The composition and heating value of these feedstock have been reported on “as received” bases (ar) according to the definition used in Phyllis database and used as input for the model. Table 1 summarizes the data of the raw feedstock; for the torrefied ones the reader can refer to the reported references [7–12].

The data of the analyzed feedstock, both raw and torrefied, have been plotted in the Van Krevelen diagram (see Fig. 1) in order to highlight the variation of elemental composition (C, H, O) [13]. In addition to the analyzed feedstock, the data referring to charcoal, lignite and anthracite have been plotted as benchmark. The graph shows that the contents of hydrogen and oxygen is high for the row feedstock and low for the charcoal, lignite and anthracite. The torrefied feedstock data lays on intermediate position; the points are closer to the charcoal increasing the torrefaction temperature and the time that wood is exposed to torrefaction. In order to compare biomass with different torrefaction temperature and torrefaction time, an integrated index, defined as torrefaction severity factor (TSF), has been calculated for each torrefied feedstock:

$$\mathrm{TSF} = \log\left[\mathrm{t}_{\mathrm{tor}} \cdot \exp\left(\frac{\mathrm{T}_{tor} + \mathrm{T}_{ref}}{14.75}\right)\right] \tag{1}$$

where $\mathrm{t}_{\mathrm{tor}}$ is the torrefaction time, $\mathrm{T}_{\mathrm{tor}}$ is the torrefaction temperature and $\mathrm{T}_{\mathrm{ref}}$ is the reference temperature (100 °C) [14].

Plant Simulations

The considered plant layouts are schematically presented in Fig. 2. The syngas production section takes into account different process options: pyrolysis, air gasification and steam gasification. If the process is endothermic the heat is provided by a burner (fed through a syngas spilling), otherwise the heat is supposed to be lost. For steam gasification the vapour is produced by a steam generator, fed through a syngas spilling. For the gasification process the pressure inside the gasifier is assumed to be atmospheric. Before feeding the CHP, syngas is piped through heat recovery and clean-up sections. Efficiency of the gasifier has been calculated considering the gasifier control volume ($\mathrm{CV}_{\mathrm{gasif}}$) as:

$$\eta_{gasif} = \frac{LHV_{syngas} \cdot Q_{v,syngas} + P_{th,recovery}}{LHV_{biom} \cdot Q_{m,biom}} \tag{2}$$

where LHV_{syngas} is the lower heating value of dry syngas, $Q_{v,syngas}$ is the volume flow rate of syngas that feeds the CHP and $P_{th,recovery}$ is the thermal power recovered from the heat exchanger between gasifier and clean-up.

The gasification section has been coupled with a combined heat and power production system (CHP). A model

Table 1 Composition and heating value of the considered raw biomasses

ID	Biomass	Moisture (%wt$_{ar}$)	Ash	C	H	O	N	LHV (MJ/kg$_{ar}$)	Refs.
1	Pine wood chips	6.69	0.25	44.03	6.20	42.68	0.16	16.945	[9]
2	Logging residue chips	7.88	1.62	43.19	5.66	41.27	0.39	17.351	
3	Reed canary grass	4.99	12.25	43.24	6.05	33.20	0.27	17.226	[8]
4	Wheat straw	4.36	17.63	39.85	5.73	31.77	0.67	16.848	
5	Willow	2.89	10.73	44.67	5.82	35.72	0.18	18.140	
6	Pine	5.10	0.13	44.17	6.07	44.46	0.06	16.287	
7	Bagasse	4.40	2.14	41.89	5.42	45.91	0.23	14.586	[7]
8	Birch	5.40	0.47	42.83	5.84	45.37	0.09	15.451	

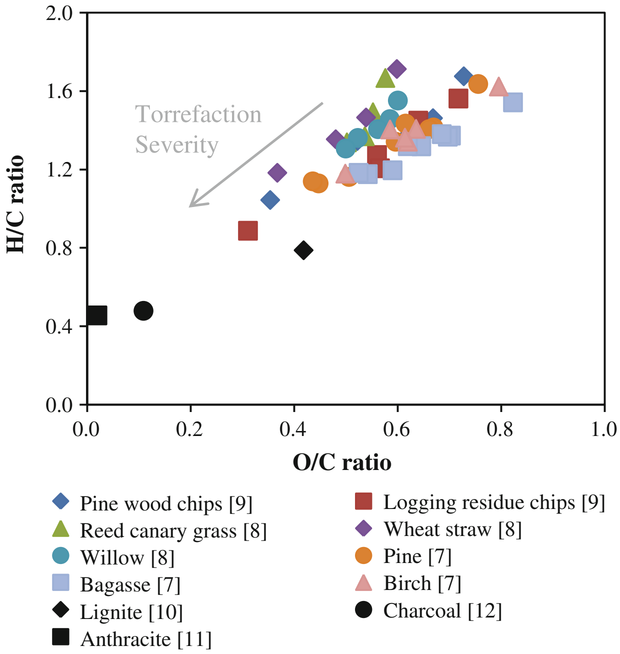

Fig. 1 Van Krevelen diagram for torrefied wood with different torrefaction pre-treatment, untreated wood, lignite, charcoal and anthracite

has been developed in Matlab environment to simulate the operation of the system. NASA polynomials implemented in Cantera have been adopted for the thermodynamic analysis of the gas and water fluxes. The whole model consists of several subroutines (one for each plant stage), represented by objects that interact with the others. Each object has been modelled by means of a different code (i.e., s-function). Simulink object-oriented language has been used for the integration of the different stages of the whole power plant.

Synthesis gas coming from gasification of biomass is assumed to be exploited in three different power plant layouts for combined heat and power production (CHP). All the conversion processes relevant to the CHP systems are assumed as ideal.

For the first layout (Fig. 3a) an internal combustion engine (ICE) has been considered. In particular, it has been implemented the Otto cycle that can exploit synthesis gas without any significant modification to the engine structure. Volume ratio in the isentropic compression has been fixed at 10. Electrical power results from the expansion stroke reduced by the compression power. The cylinder has been considered adiabatic hence the thermal power comes only from exhaust gas cooling.

The second layout (Fig. 3b) foresees a gas turbine (GT). Gas turbines usually are fuelled with methane for stationary energy production applications but they can also be fed with synthesis gas. Even though the main difference between syngas and methane is the lower heating value, gas turbines usually operates at high air excess, so that a dilution in the fuel should not affect significantly the overall energy performance. The pressure ratio in the isentropic compression has been optimized for the maximum work output. Electrical power comes from the expansion phase reduced by the compression power. The gas turbine components have been considered adiabatic, hence the thermal power comes only from exhaust gas cooling.

The third layout considers a combined power plant for heat and power production (Fig. 3c). It consists of a gas turbine (GT) coupled with a steam turbine (ST) through a heat recovery steam generator (HRSG). Concerning the gas turbine, the working phases and parameters are the same as the previous layout. Steam turbine is based on the Hirn cycle that has been modelled in this work considering the ideal transformations. The condensation pressure is assumed equal to 0.06 bar and the thermal power exchanged by the condenser is supposed to be completely recovered. The evaporation pressure has been calculated to completely exploit the thermal energy coming from the exhaust gas cooling of the gas turbine.

The final clean-up section of the power plant is common for all the technologies involved in the analysis. The exhaust from CHP passes through an heat exchanger to be cooled down to 150 °C. The temperature has been

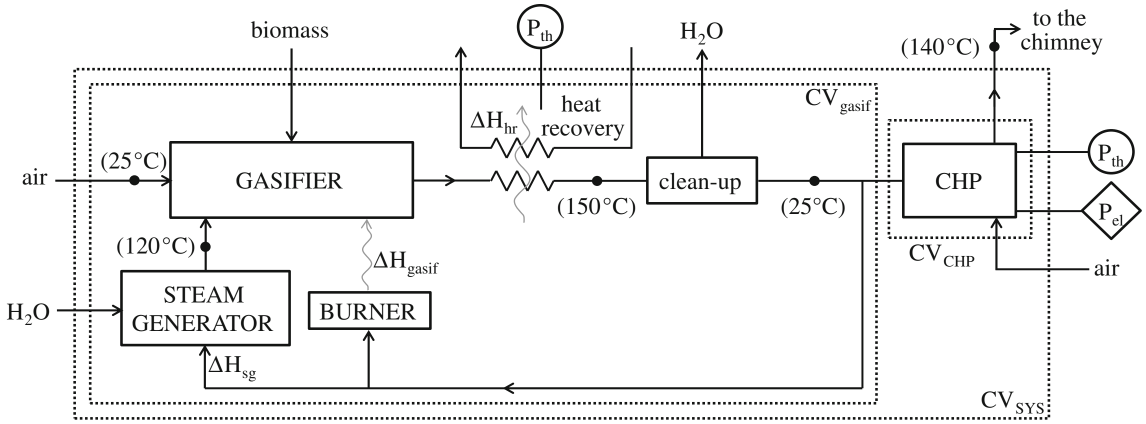

Fig. 2 Schematic diagram of the plant layout

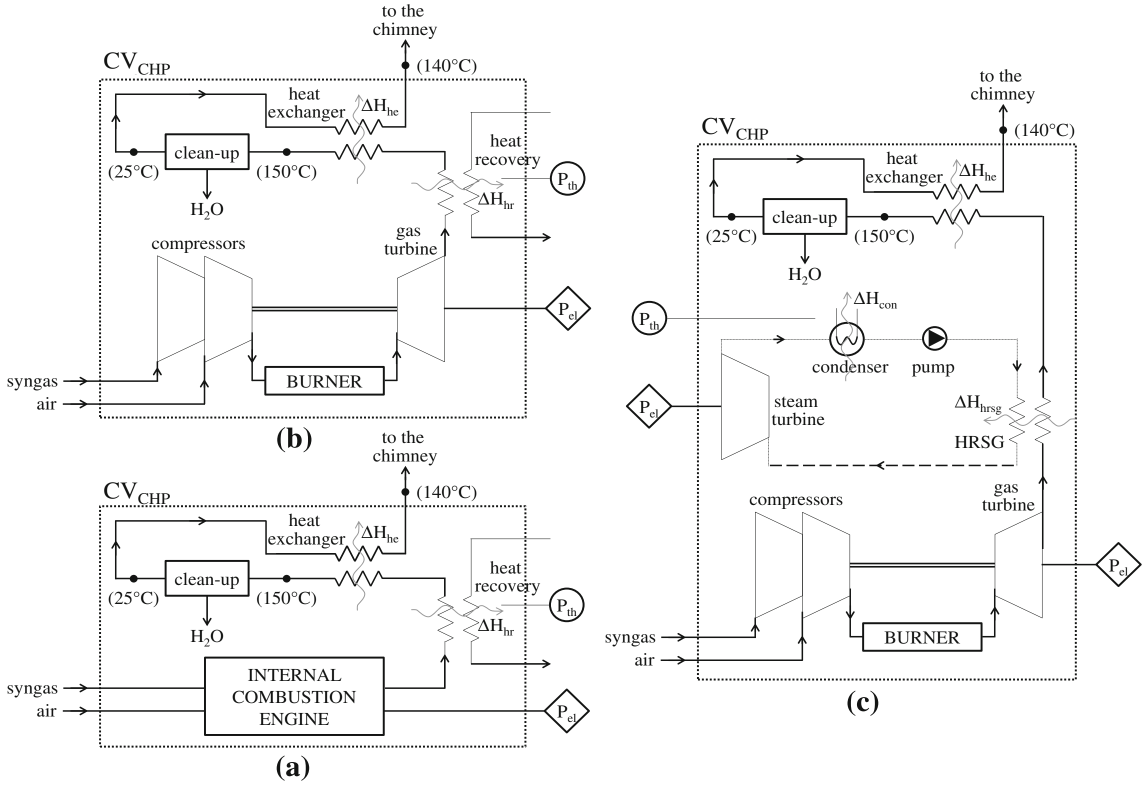

Fig. 3 Considered CHP units: **a** internal combustion engine, **b** gas turbine and **c** combined cycle gas turbine

chosen in order to avoid condensation of the tar that would clog up the heat exchanger. The proper clean-up occurs in a condenser that cools the exhaust down to 25 °C, equipped with a condensate collector. Tar and water are then disposed. Purified exhaust gas is ready to be heated up to 140 °C through a heat exchanger and sent to the chimney. The main parameters adopted for the power plant layout are summarized in Table 2; the variation range is reported for the parameters that have been optimized.

Electrical and global efficiencies have been calculated for each layout considering the system control volume (CV_{SYS}) as:

$$\eta_{el} = \frac{P_{el}}{LHV_{biom} \cdot Q_{m,biom}} \tag{3}$$

$$\eta_{gl} = \frac{P_{el} + P_{th}}{LHV_{biom} \cdot Q_{m,biom}} \tag{4}$$

where LHV_{biom} is the lower heating value of biomass, $Q_{m,biom}$ is the biomass flow rate, $P_{el}$is the electrical power generated

Table 2 Parameters adopted for the power plant layouts

Plant unit	Process parameters	Value
Gasifier	Temperature, air (in gasifier)	25 °C
	Temperature, steam (in gasifier)	120 °C
	Temperature, syngas (in clean-up)	150 °C
	Temperature, syngas (out clean-up)	25 °C
	Temperature, syngas (in CHP)	25 °C
ICE	Compression ratio	10
GT	Pressure ratio	3 ÷ 15
Rankine	Condensation pressure	0.06 bar
	Evaporation pressure	10 ÷ 58 bar
HRSG	Approach point temperature	55 °C
	Pinch point temperature	20 °C
Chimney	Temperature, exhaust (out chimney)	140 °C

by the CHP and P_{th} is the thermal power recovered from both the gasifier and the CHP.

Each layout has been simulated varying biomass specie, torrefaction conditions and gasification parameters. For each case a parity factor (PF) has been defined and calculated. It is a non-dimensional parameter representing the maximum energy amount versus the energy content of the biomass that can be used for the torrefaction pre-treatment. It is defined as the difference between the global energy output from a raw and a torrefied feedstock divided by the biomass energy input:

$$PF = \frac{P^{Torrefied}_{out,chp} - P^{NotTorrefied}_{out,chp}}{LHV_{biom}\cdot Q_{m,biom}} = \eta^{T}_{gl}\cdot\frac{LHV^{T}_{biom}}{LHV^{NT}_{biom}}\cdot\frac{Q^{T}_{m,biom}}{Q^{NT}_{m,biom}} - \eta^{NT}_{gl} \qquad (5)$$

where η_{gl} is the global efficiency (electrical and thermal) of the whole power plant, LHV_{biom} is the lower heating value, $Q_{m,biom}$ is the mass rate of biomass. The superscripts of all the variables refer to torrefied feedstock (T) or not-torrefied feedstock (NT). Negative results of the index mean that the torrefaction pre-treatment does not lead to energy benefits.

Results and Discussion

Torrefaction Data Analysis

By means of the torrefaction severity factor (TSF) it is possible to compare the heating value and mass yield for feedstock with different torrefaction conditions (see Fig. 4). The mass yield (see Fig. 4a) has the opposite trend compared to the heating value (see Fig. 4b); the mass yield decreases and the heating value increases with the TSF. The highest value of mass yield refers to the wheat straw with 43 % that corresponds to 57 % of mass loss. The

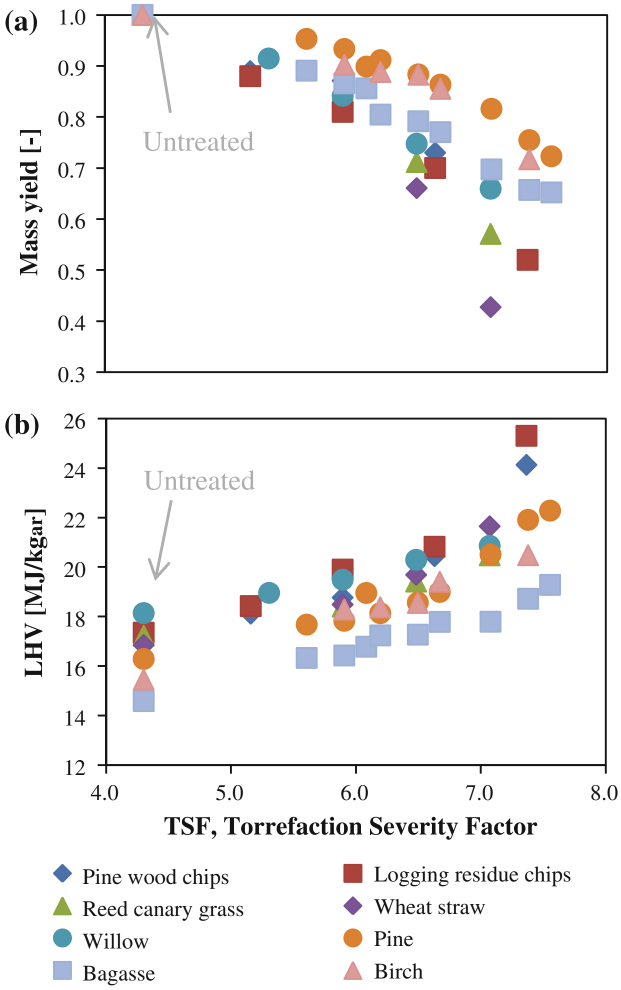

Fig. 4 Mass yield **a** and low heating value **b** depending on the torrefaction severity factor for several biomasses

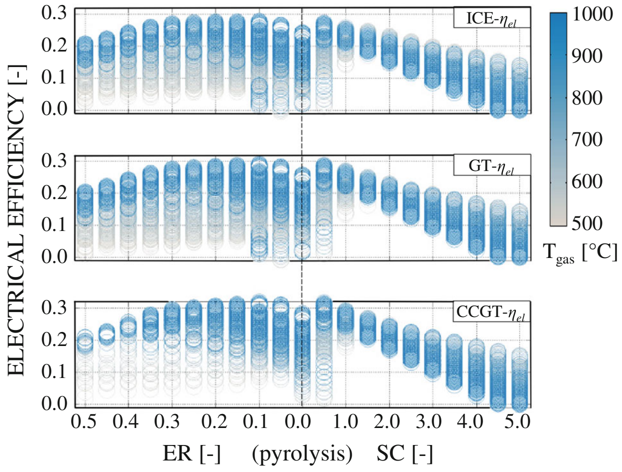

Fig. 5 Scatter plot of the electrical efficiency for each plant layout considering all the cases (biomass typology, torrefaction and gasification conditions); dot dimensions are proportional to the gasification temperature

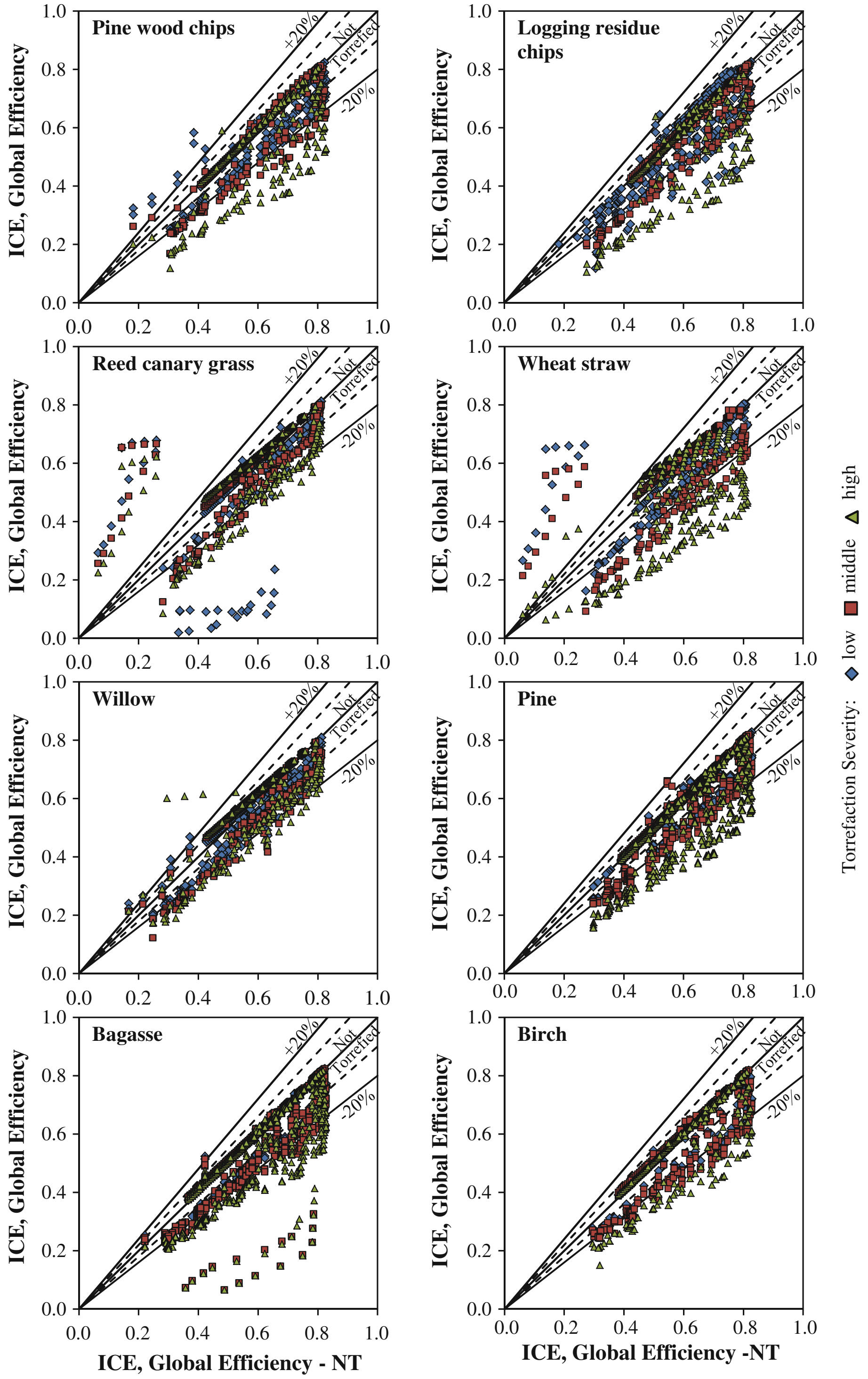

Fig. 6 Global efficiency for the ICE layout fed by row feedstock and the same layout fed by torrefied feedstock; the results are shown for several feedstock

highest increase of heating value due to the torrefaction treatment refers to the logging residue chips with an increase of 47 %. These effects on mass yield and heating value are mainly due to the de-watering, de-polymerisation, de-volatilization and carbonization of the feedstock.

Simulation Data Analysis

The global electrical efficiencies is reported in Fig. 5 for all the simulated plant configurations clustered for the three power plant solutions: internal combustion engine (ICE), gas turbine (GT), combined cycle gas turbine (CCGT). Making reference to air gasification, the electrical efficiency assumes high values in correspondence with ER between 0.1 and 0.3 and the gasification temperature seems to have an enhancing effect. A local minimum of the electrical efficiency occurs for the pyrolysis conditions. The general behaviour here described is due to the lower conversion degree of carbon into syngas. In fact, due to the hypothesis of this work, solid carbon is not exploited to produce energy. Considering the steam gasification processes, the electrical efficiency assumes high values in correspondence with SC around 0.5 and gasification temperature around 750 °C.

The torrefaction pre-treatment is an additional process that does not always lead to obtain energy benefits in the biomass conversion process. The Fig. 6 compares the global efficiency for the ICE layout fed by row feedstock and the same layout fed by torrefied feedstock; the results are shown for several feedstock. In general, for all the considered biomasses, torrefaction pre-treatment allows to reach an higher electrical efficiencies of the whole power plant but the increase does not exceed 10 % for optimized configurations. Focusing on the results for wheat straw and reed canary grass, Fig. 6 shows that for low-efficiency conversion processes it is possible to obtain a considerable increase of the global efficiency introducing a torrefaction pre-treatment in the energetic chain.

The parity factor (PF) with respect to the torrefaction severity factor (TSF) and clustered for different feedstock is then plotted in Fig. 7; the data refers to a power plant based on internal combustion engine. For the great majority of the feedstocks, an high severity factor leads to worsen the energy balance of a biomass conversion process. Referring to grass-crops (reed canary grass, wheat straw) it is possible to define an optimal torrefaction conditions that correspond with a middle torrefaction treatment of the feedstock.

Figure 8a compares the electrical efficiency of the analysed prime movers (ICE, GT, CCGT) that maximize the electrical generation; the results are shown for all the considered feedstock. Considering the optimal operational conditions of the analysed power plants, the internal combustion engine is the technology that shows the lowest electrical efficiency but there is probably still room for the optimization of the compression ratio. The combine cycle gas turbine shows the highest electrical efficiency, since the steam turbine generates further electricity exploiting the discarded heat of the gas turbine. The results are clustered in the graph for the pyrolisis, the air gasification and the steam gasification. Optimal operational condition for the pyrolisis process corresponds with a gasification temperature of 900–1,000 °C and using not torrefied feedstock. This process is less efficient than air and steam gasification and it probably leads to low conversion of carbon into syngas. The air gasification process is optimized for gasification temperature of 800–850 °C, ER equals to 0.1–0.2 and using torrefied biomass. The steam gasification process is optimized for gasification temperature of 750–900 °C, SC equals to 0.5 and using biomass with a middle degree of torrefaction.

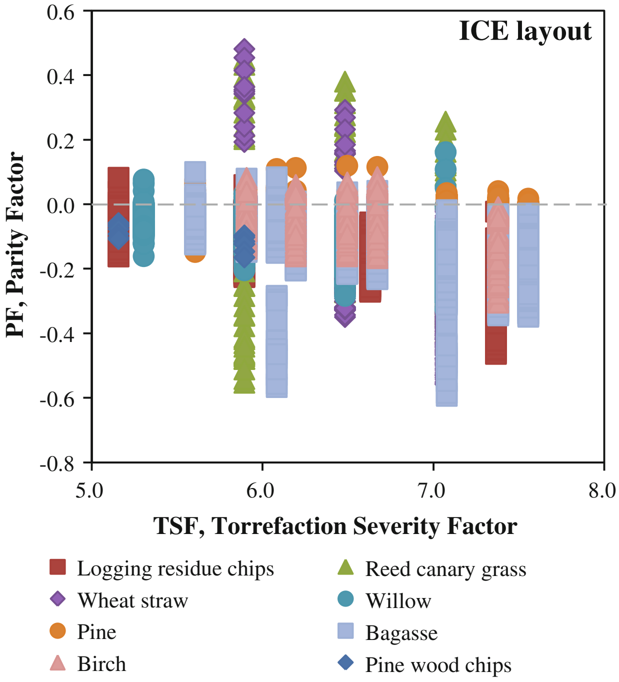

Fig. 7 The parity factor depending on the torrefaction severity factor for the analysed feedstock; the results refer to the ICE layout

Figure 8b reports a comparison of the power plant layouts that maximize the parity factor. The results are clustered in the graph for the pyrolisis, the air gasification and the steam gasification; optimal operational conditions correspond with the values already mentioned above. The ICE layout seems to reach considerable benefits introducing a slight torrefaction pre-treatment if the prime mover is coupled with an air gasifier with low value of the equivalence ratio.

Conclusions

The benefit of torrefaction for the gasification process is widely demonstrated [15]. This work extend the analysis at the system scale considering three different CHP layouts. The results seem to confirm that torrefaction pre-treatment could enhance the global energy efficiency—also considering the CHP section—for selected process operating conditions (partial oxidation with ER from 0.1 to 0.3 and steam gasification with SC around 0.5, for the present study). Finally, it seems that grass-crops can reach considerable

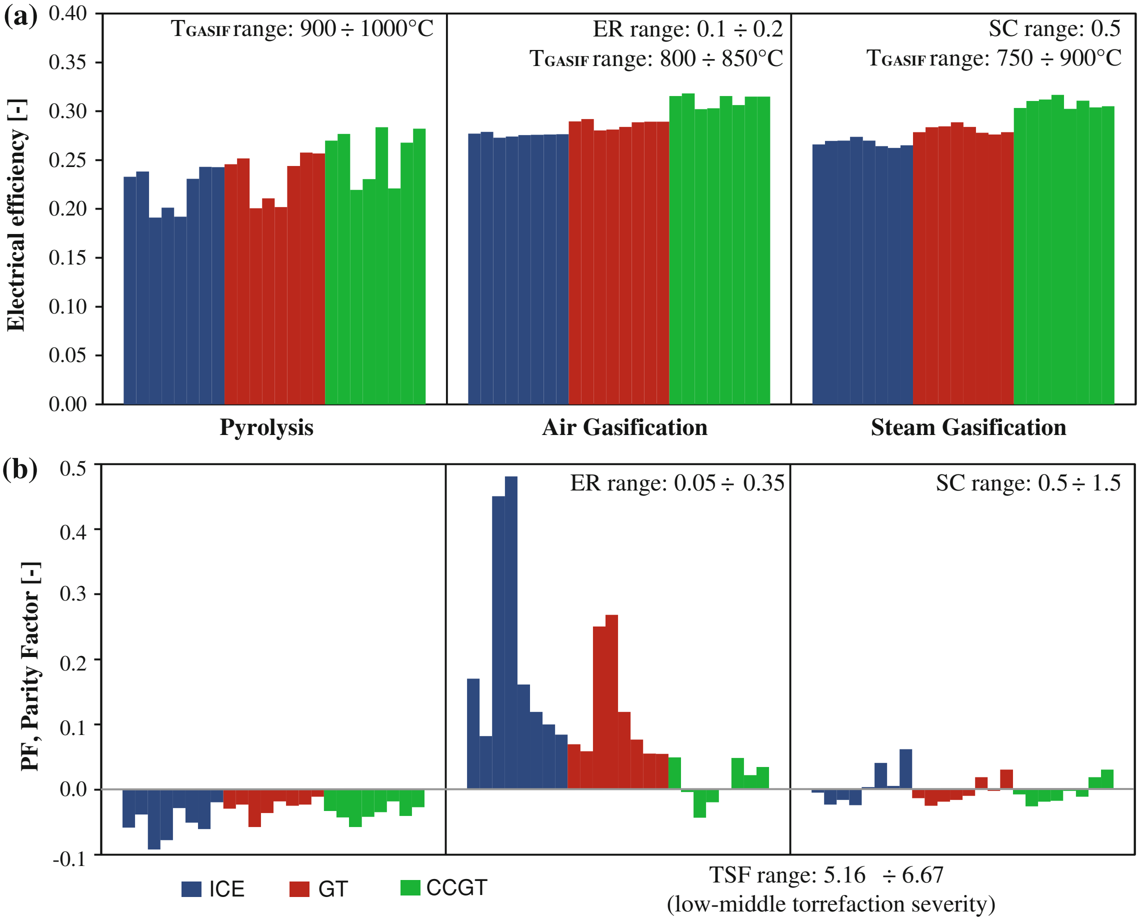

Fig. 8 Maximum electrical efficiency **a** and maximum parity factor **b** for each considered power plant layout and gasification process; the results are ordered for the following feedstock: pine wood chips, logging residue chips, reed canary grass, wheat straw, willow, pine, bagasse, birch

benefits introducing a torrefaction pre-treatment stage in the biomass conversion process. In order to confirm these results, experimental validation and a larger feedstock dataset are required.

References

1. Baratieri, M., Baggio, P., Bosio, B., Grigiante, M., Longo, G.A.: The use of biomass syngas in IC engines and CCGT plants: A comparative analysis. Appl. Therm. Eng. **29**, 3309–3318 (2009)
2. Fagbenle, R.L., Oguaka, A.B.C., Olakoyejo, O.T.: A thermodynamic analysis of a biogas-fired integrated gasification steam injected gas turbine (BIG/STIG) plant. Appl. Therm. Eng. **27**, 2220–2225 (2007)
3. Ahmed, T.Y., Ahmad, M.M., Yusup, S., Inayat, A., Khan, Z.: Mathematical and computational approaches for design of biomass gasification for hydrogen production: A review. Renew. Sust. Energy Rev. **16**, 2304–2315 (2012)
4. Goodwin, D.: Cantera: an object-oriented software toolkit for chemical kinetics, thermodynamics, and transport processes
5. Baratieri, M., Baggio, P., Fiori, L., Grigiante, M.: Biomass as an energy source: Thermodynamic constraints on the performance of the conversion process. Biores. Tech. **99**, 7063–7073 (2008)
6. Chew, J.J., Doshi, V.: Recent advances in biomass pretreatment—Torrefaction fundamentals and technology. Renew. Sust. Energy Rev. **15**, 4212–4222 (2011)
7. Pach, M., Zanzi, R., Björnbom, E.: Torrefied Biomass a Substitute for Wood and Charcoal. 6th Asia-Pacific International Symposium on Combustion and Energy Utilization., Kuala Lumpur, Malaysia (2002)
8. Bridgeman, T.G., Jones, J.M., Shield, I., Williams, P.T.: Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. Fuel **87**, 844–856 (2008)
9. Phanphanich, M., Mani, S.: Impact of torrefaction on the grindability and fuel characteristics of forest biomass. Biores. Tech. **102**, 1246–1253 (2011)
10. Nikkhah, K., Bakhshi, N.N., MacDonald, D.G.: Co-pyrolysis of various biomass materials and coals in a quartz semi-batch reactor. Energy from biomass and wastes XVI (Ed. D.L.Klass). pp. pp. 857–902 (1993)
11. Van Doorn, J.: Combined combustion of biomass, municipal sewage sludge and coal in an atmospheric fluidized bed installation. Fuel Energy Abstr. **37**, 204 (1996)
12. Pentananunt, R., Rahman, A.N.M.M., Bhattacharya, S.C.: Upgrading of biomass by means of torrefaction. Energy **15**, 1175–1179 (1990)
13. Boersma, A.R.: Torrefaction for biomass co-firing in existing coal-fired power stations. (2005)

14. Lee, J.-W., Kim, Y.-H., Lee, S.-M., Lee, H.-W.: Optimizing the torrefaction of mixed softwood by response surface methodology for biomass upgrading to high energy density. Biores. Tech. **116**, 471–476 (2012)
15. Prins, M.J., Ptasinski, K.J., Janssen, F.J.J.G.: More efficient biomass gasification via torrefaction. Energy **31**, 3458–3470 (2006)